ACCOUNTING FOR SOIL ORGANIC CARBON IN ESTIMATING SOIL HYDRAULIC PROPERTIES

An Undergraduate Research Scholars Thesis

by

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ABSTRACT

Accounting for Soil Organic Carbon in Estimating Hydraulic Properties. (May 2015)

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Soil scientists and agronomists know that increases in soil organic matter change the way that soil and water interact. Soil high in organic matter develop stronger aggregation and soil structure resulting in increased porosity, water holding capacity, and infiltration rates. Changes in land use and climate alter soil organic matter and subsequently soil hydraulic properties. However, land surface and hydrology models generally use soil hydraulic properties based only on soil texture without information on soil organic matter. The goal for this project is to improve available soil information for hydrology modeling by adding organic matter content into prediction functions of soil hydraulic properties, therefore making more representative predictions of how soils interact with water. Porosity, hydraulic conductivity and soil water contents at field capacity (Θ_{FC})and permanent wilting point (Θ_{WP})were estimated using multiple linear regression that incorporate measurements of soil texture and organic matter for A (surface) horizons. Data on soils in the National Cooperative Soil Characterization Database were used to create these functions for Texas and neighboring states and then compared to existing pedotransfer functions. The results agree with the literature that soil organic matter is a statistically significant component, along with texture, in predicting porosity, field capacity, and permanent wilting point; however, the change in predicted values is not functionally different

except when predicting porosity. Because newly predicted porosity values were different, estimates of saturated hydraulic conductivity were also worth recalculating using organic matter. The results are attributed to the way field capacity is measured on soil clods rather than soil volumes that include inter-pedal pores. Though we know that soil organic matter has a strong link to soil structure, the databases available do not contain the type of information needed to fully represent the relationship between soil organic matter, soil structure, and soil water relations.

CHAPTER I

INTRODUCTION

The majority of spatially distributed hydrologic and land surface models require two types of soil information: 1) a map of soil properties and 2) a corresponding lookup table of soil hydraulic properties. Soil hydraulic properties are estimates from empirical models based on soil texture because actual measurements of soil hydraulic properties are difficult to measure due to time, resources, and field conditions. These empirical models are called pedotransfer functions, and are created using large data bases where soil texture and sometime organic matter are measured along with soil hydraulic properties. For example, Saxton and Rawls (2006) is an update of previously, widely cited pedotransfer functions and is based on a soil database for soils of the United States.

Organic matter percentage is not a property that these lookup tables often consider because soil organic matter is a dynamic soil property that changes with land use and climate, while soil texture is temporally constant. Currently, some lookup tables, use pedotransfer functions based only on sand and clay percentage; however, organic matter is known to significantly affect the soil hydraulic properties (Brady & Weil, 2010). Hydraulic properties that are measured in large databases include soil water content at wilting point (-1500 kPa) and field capacity (-33 kPa), as well as, soil porosity which is a proxy for water held by the soil at saturation (0 kPa). Subsequently, these properties are converted to other hydraulic properties such as saturated hydraulic conductivity and coefficients in the soil moisture release curve (Campbell, 1974). Saturated hydraulic conductivity and coefficients for the soil moisture release curve are used in simulating water infiltration, redistribution, and evapotranspiration through and from the soil; however, if these properties are inaccurate it adds additional error to the output of the models.

The overall objective of this project is to improve performance of land surface models and hydraulic models by incorporating soil organic matter into lookup tables containing hydraulic properties for Texas and neighboring state soils. Specific soil properties to be analyzed for significant improvement by the addition of soil organic matter are soil moisture at wilting point and field capacity, soil porosity, and saturated hydraulic conductivity, as these were found to be most influential to changing outputs of land surface models (Morgan & Kishne, 2013).

The direction of flow (infiltration and redistribution) of water through the soil is governed by gradients in the soil matric potential. Soil matric potential describes forces between water molecules and solid particles; more negative matric potentials indicate drier soils. The two soil matric potentials used to determine available water are wilting point (-1500 kPa) and field capacity (-33 kPa). Wilting point is an estimate of the soil water potential at which plants will permanently wilt whereas; field capacity is approximately the water potential 48 hours after the soil becomes saturated following a rainfall event. Plants generally use the water that is between field capacity and permanent wilting point. Because matric potential is used to define the amount of energy a plant requires to pull water out of the soil, the relationship between matric potential and volumetric soil moisture is necessary to model soil-plant-water dynamics (Brady & Weil, 2010). This relationship changes significantly with additions and losses of soil organic matter (Brady & Weil, 2010). Bloodworth (2003) found that adding soil organic matter to predict water content has improved predictions by up to 20%.

Increases in soil organic matter has been found to affect wilting point and field capacity depending on the soil texture. Hudson (1994) found that within each soil textural class, increases in organic matter increased the water held at field capacity. Hudson (1994) analyzed sands, silt loams, and silty clay loams with varying organic matter using regression analysis on each texture category with everything else held constant. Organic matter contents between 1-3% were shown to double the available water capacity. In soils with more than 4% organic matter, the increase in organic matter accounts for 60% of available water holding capacity (Hudson, 1994). Soils with organic matter have a more developed structure, in comparison to soils without organic matter; therefore more inter-pedal (between structural units) macropores and more water held that is available for plant use.

Porosity is the percentage of the total soil bulk not occupied by solid particles. The rate of water infiltration into the soil and the amount of water the soil can hold are both directly influenced by the porosity, or the amount of void space between solid soil particles. There are two types of pores: macropores and micropores. Macropores are the principal channels for infiltration and drainage of water, aeration, and water held that is available to the plant. Micropores are intra-aggregate capillaries that contribute to water and solute retention (Hillel, 1998). High clay soils are different in water holding capacity due to the shrink/swell potential, aggregation, dispersion, compaction, and cracking (Hillel, 1998). Increases in soil organic matter are expected to increase soil porosity because soil organic matter improves soil structure and aggregation, increasing quantity of macropores, which is a component to porosity (Brady & Weil, 2010).

Saturated hydraulic conductivity is a measure of the ability of soil to transmit water. Hydraulic conductivity is affected by gravity and pressure or suction gradients in soil which is affected by soil structure and texture. While highly porous, fractured, or aggregated soils have high hydraulic conductivities, pores size distribution is also an important factor. Sandy soils have larger pores than clay and therefore have a higher hydraulic conductivity. Due to various chemical, physical, and biological processes, hydraulic conductivity can change as water infiltrates soil pores over time. Since we believe porosity estimates to be improved by soil organic matter, hydraulic conductivity estimates will also be improved (Morgan & Kishne, 2013).

The Natural Resources Conservation Service (NRCS) has a large data base of soil pedons collected across the United States and Texas. This database entails the Rapid Carbon Assessment (RaCa) data set is the largest geo-referenced soil carbon dataset, managed by U.S. Department of Agriculture (USDA) and NRCS, collected with aim to "help producers and planners estimate the impacts of conservation practices on soil carbon levels" (USDA and NRCS, 2013). NRCS soil scientists took 148,000 individual soil samples across the United States, where 6,800 samples are points across Texas and evaluated for soil carbon content. The information from the samples was then compiled into a file publicly available from the USDA website. In short, the RaCa dataset provides a geo-referenced snapshot of the amount of carbon each soil type contains (USDA and NRCS, 2013). Because RaCa provides a recent snap-shot of soil organic matter in the United States, it could be used to improve estimates of soil physical properties if soil organic matter shows to improve the estimates.

The overall goal for this project is to improve soil parametrization in hydrologic modeling and land surface modeling by adding soil organic matter into prediction functions of soil hydraulic properties; thereby, generating more representative predictions of how soils interact with water, carbon, and energy. The following specific objectives were addressed, (1) document available pedotransfer functions for soil hydraulic properties that include organic matter and soil texture, (2) develop a new lookup table built from soil texture and soil organic matter measurements across Texas, and (3) compare hydraulic properties from published lookup tables and the newly developed table that includes soil organic matter. Upon completion of these achievements we will have an improved look up table of soil hydraulic properties and/or better understanding of the limitations of the databases of soil properties. If soil organic matter measurements improve on change estimates of soil hydraulic properties, then this project will be continued by incorporating RaCa soil organic matter measurements to provide a spatial map of soil hydraulic properties.

CHAPTER II

METHODS

The dataset used in this study was obtained from the National Cooperative Soil Characterization Database (NCSCD) and contains approximately 1000 geo-referenced pedons (6749 soil samples), smallest unit or volume of soil that contains all the soil horizons of a particular soil type, collected across Texas and adjoining states that share Major Land Resource Areas with Texas. This dataset was compiled to create the revised Noah-MP soil parameters mainly for the state of Texas (Morgan and Kishne, 2013). For this study, we used the following soil properties in the dataset: bulk density, total carbon, inorganic carbon, clay content, sand content, horizon nomenclature, top horizon depth, lower horizon depth, texture category, and gravimetric soil water contents at wilting point and field capacity.

The first step to addressing the goals of this project was to refine the dataset to reflect only epipedons (the soil surface horizons demonstrating an accumulation of organic matter). The following criteria were used to extract the data set: A horizon nomenclature, no buried horizons (Ab –horizon designation), and top horizon depth less than 31 cm. Of these extracted data, we further investigated soils with greater than 1 % total matter and no inorganic matter values for quality control. The concern was that some of the high total carbon values were associated with carbonates. Of these soils, three were removed because the official soil series description indicated strongly effervescent surface horizons. Finally we end up having 700 soil samples out of the 4749 that are qualified for our study.

The 700 remaining soil samples were differentiated into four general texture categories: sands, loams, clay loams, and clays. The standard USDA soil textural triangle was reclassified into these four general textural categories to have more samples in each class for statistical comparison. Sands in the general class included sands and loamy sand in the USDA textural classification. Similarly loams included silt loams, loams and silts; clay loam included sandy clay loam, clay loam, and silty clay loam; and clays included silty clay, clay, and sandy clay. The sands contained 264 samples; the loams contained 153 samples; the clay loams contained 142 samples; the clays contained 141 samples (Table 1).

The data set of 700 soil samples was modified to have appropriate units needed for the pedotransfer functions (Table 2). In the dataset, soil water contents at -33 kPA and -1500 kPa were reported in gravimetric units. These gravimetric water contents were converted to volumetric by multiplying gravimetric water content and soil bulk density (ρ_b), measured using the clod method, and assuming the density of water to be 1 g cm^{-3} (National Cooperative Soil Survey, 2012). The conversion resulted in measured values of volumetric water contents at field capacity and at wilting point. Volumetric water content at saturation was assumed to be equal to porosity, which was calculated using ρ_b and assuming a particle density (ρ_s) of 2.65 g cm^{-3}. Soil organic carbon was calculated by subtracting inorganic carbon from total carbon. In non-calcareous soils, inorganic carbon was assumed to be zero. To convert to soil organic matter (SOM), organic carbon is multiplied by 1.72 (Schumacher, 2002).

Because observations of soil water contents at saturation (0 kPa, or Porosity), -33 kPa (Field Capacity) and -1500 kPa (Permanent Wilting Point) are not readily available and can be very expensive to measure, a model (pedotransfer function) was developed to calculate field capacity, permanent wilting point, and porosity using more readily available data (texture and SOM). The first set of predicted hydraulic properties was calculated using pedotransfer functions from the literature. Saxton and Rawls (2006) pedotransfer functions calculate soil hydraulic properties using percent sand, clay, and SOM as independent variables. To evaluate the significance of incorporating SOM in the Saxton and Rawls (2006) pedotransfer functions, the pedotransfer functions were set up assuming both SOM to be constant (1%) and SOM to vary as in the actual measurements. The results were then compared by calculating the residual mean square error (RMSE) of the predicted hydraulic properties and the measured.

A second set of hydraulic properties prediction functions was created using the 700 soil data set. In Matlab (Ver. R2013a, MathWorks, Inc.), linear models were created using percent sand (S), clay (C), and SOM as independent variables, and the three soil water contents as dependent variables. Conceptually, each pedotransfer function relates to a soil moisture content with and without organic matter as shown in the following equations:

$$\text{Water content at } (0, -33, -1500 \text{ kPa}) = a + b{\bullet}S + c{\bullet}C \qquad (1)$$

$$(0, -33, -1500 \text{ kPa}) = a + b{\bullet}S + c{\bullet}C + d{\bullet}SOM \qquad (2)$$

where a, b, c, and d are regression coefficients.

To test whether S, C, and SOM provided significant contributions to the predictions of soil water contents, the p-values for the coefficients were determined using a generalized linear model regression (glmfit function in Matlab), and the p-value criterion of < 0.0001. Using these pedotransfer functions, RMSE of predictions and bias were compare to measured values.

Saturated hydraulic conductivity was calculated using the pedotransfer function developed by Saxton and Rawls (2006). The inputs into the function are soil moisture at saturation, and field capacity. To analyze the effect of organic matter on hydraulic conductivity, the field capacity predictions with and without organic matter from Saxton and Rawls (2006) as well as for the newly developed functions were used as the inputs. The calculation of soil moisture at saturation by Saxton and Rawls (2006) pedotransfer function is over estimated therefore the saturated hydraulic conductivity is also over estimated.

Table 1. Summary statistics for the 700 surface samples from the dataset by texture categories.

	Sand	Clay	$CaCO_3$	SOM[†]	Field Capacity	Wilting Point	Porosity	ρ_b
	---------------	%	---------------		---------------	cm^3cm^{-3}	---------------	gcm^{-3}
Sands								
Mean	74.8	8.4	1.7	0.81	0.18	0.06	0.42	1.53
SD	13.3	4.9	3.0	0.72	0.07	0.03	0.05	0.12
Min	46.0	0.0	0.0	0.00	0.03	0.01	0.27	1.09
Max	99.2	19.5	20.0	4.74	0.40	0.29	0.59	1.94
Loams								
Mean	35.5	17.7	12.0	1.73	0.27	0.12	0.47	1.40
SD	12.8	4.9	19.4	1.13	0.06	0.03	0.06	0.15
Min	2.7	4.1	0.0	0.12	0.14	0.02	0.35	0.84
Max	51.9	26.9	76.0	6.60	0.41	0.21	0.68	1.72
Clay loams								
Mean	30.3	31.0	13.9	2.13	0.33	0.18	0.50	1.34
SD	16.7	5.0	17.9	1.41	0.06	0.04	0.05	0.13
Min	2.1	20.3	0.0	0.15	0.17	0.08	0.38	0.99
Max	65.1	39.6	71.0	8.86	0.55	0.34	0.63	1.63
Clays								
Mean	12.9	54.1	9.4	2.74	0.42	0.29	0.54	1.21
SD	9.8	11.2	13.6	1.64	0.06	0.06	0.05	0.14
Min	0.0	36.8	0.0	0.03	0.16	0.13	0.40	0.79
Max	47.2	87.9	57.0	8.12	0.58	0.51	0.70	1.58

[†] SOM is soil organic matter; and ρ_b is bulk density of soil clods.

Table 2. Summary statistics of the 700 surface horizons from the dataset.

	Sand	Clay	$CaCO_3$	SOM[†]	Field Capacity	Wilting Point	Porosity	ρ_b
	------------------%----------------------				------------------cm^3cm^{-3}---------------			gcm^{-3}
Mean	44.7	24.2	9.1	1.67	0.27	0.15	0.47	1.40
SD	28.0	18.4	15.3	1.40	0.11	0.09	0.07	0.18
Min	0.0	0.0	0.0	0.0	0.03	0.01	0.27	0.79
Max	99.2	87.9	76.0	8.86	0.58	0.51	0.70	1.94

[†] SOM is soil organic matter; and ρ_b is bulk density of soil clods.

CHAPTER III

RESULTS

The pedotransfer functions found in Saxton and Rawls (2006) were developed from soils collected across the United States, hence geographically represent Texas and uses a comprehensive set of soils data. The pedotransfer function in Saxton and Rawls (2006) were developed from the USDA NRCS National Soil Characterization database, which contains pedons from all across the United States. Saxton and Rawls (2006) pedotransfer functions use percent sand, clay, and soil organic matter as predictors for porosity and volumetric water content at field capacity and permanent wilting point. To look at the effect of organic matter on predictions of water contents of the Texas dataset, the Saxton and Rawls (2006) pedotransfer functions were used to predicted water content.

The predictions using the Saxton and Rawls (2006) pedotransfer functions were compared to the predictions by the newly developed pedotransfer functions. The newly developed pedotransfer functions predictions were made using the following equations:

$$\text{Field Capacity } (-33\text{kPa}) = 0.2750 - 0.0016 \cdot S + 0.0031 \cdot C$$

$$(-33\text{kPa}) = 0.2650 - 0.0015 \cdot S + 0.0030 \cdot C + 0.0059 \cdot SOM$$

$$\text{Permanent Wilting Point } (-1500\text{kPa}) = 0.0529 - 0.00034110 \cdot S + 0.0044 \cdot C$$

$$(-1500\text{kPa}) = 0.0413 - 0.00024895 \cdot S + 0.0043 \cdot C + 0.0068 \cdot SOM$$

$$\text{Porosity } (0\text{kPa}) = 0.04532 - 0.00054681 \cdot S + 0.0018 \cdot C$$

$$(0\text{kPa}) = 0.4245 - 0.00031848 \cdot S + 0.0014 \cdot C + 0.0169 \cdot SOM$$

where sand (S), clay (C) are fractions and soil organic matter (SOM) is a percent.

In the predictions of soil moisture content, as well as Saxton and Rawls (2006) predictions, only porosity was significantly improved by including soil organic matter (Table 3 and 4). Field capacity and permanent wilting point were improved, but the improvement was minimal (Fig 1 and 2).

The predicted water contents are plotted as a function of clay with organic matter being constant (1%) and with organic matter fluctuating based on measured values (Fig. 1). Regardless of the water content being predicted, clay is the primary soil property that drives the effect of the prediction of water contents. As organic matter is allowed to vary, porosity and field capacity are most affected (Fig. 1). Very little variability is introduced by organic matter varying in the predictions of permanent wilting point. The literature is clear that permanent wilting point is dominated by the adsorption of water to clay minerals (Brady & Weil, 2010). The Saxton and Rawls (2006) equations with Texas data show that porosity is most affected, of the three predicted properties, by variations in organic matter, likely this is because of the strong effect of organic matter on soil bulk density. Porosity was calculated from soil bulk density measurements. On both datasets, USDA NRCS and the Texas dataset, field capacity is measured by the clod method. This method measures the water content held in a natural clod about the size of a chicken egg. We would expect that organic matter affects water held at field capacity in the interclod space, hence measurements of field capacity based on the clod method would be expected to be less sensitive to soil organic matter.

In general, allowing soil organic matter to vary, in the Saxton and Rawls (2006) predictions, did not have a numerical effect on the predictions of water contents but did on porosity (Fig. 2; Table 3). According to results in Fig. 2, organic matter had a very minimal effect on the predictions. The mean for field capacity was improved by less than 1% and the variance by 1.61%. The same pattern is observed for permeant wilting point; organic matter had a minimal improvement to the prediction. The mean was improved by less than 1% and the variance by 11%. Porosity predictions were meaningfully improved with varying organic matter (Fig. 2; Table 3). The mean was improved by 2% and the predictability of the variance was improved by 223%. As can be observed in Fig. 2, the addition or organic matter allows from more variability in the prediction as clay content changes. .

The pedotransfer functions developed using the Texas dataset results in a better correlation to the measurement because they were developed from the data—ie the validation set is not independent of the calibration set. In general, the same trends as in the Saxton and Rawls (2006) predictions were observed. The effects of organic matter on water contents are not apparent, except when evaluating the porosity prediction (Fig. 3). Permanent wilting point has the least change with the addition of organic matter. Field capacity variation can primarily be accounted for by clay content. Including SOM in the porosity prediction shows increased variability with clay content. Though we expected more variability in sandier soils, Fig. 2 shows equal variability in porosity predictions across all clay contents.

Comparing prediction values of Saxton and Rawls and the measured data in the Texas dataset provides some insight to the prediction performance of Saxton and Rawls (2006). A perfect mat between predicted and measured demonstrates a perfect prediction along the one-to one line. Scatter about the one-to-one line demonstrates the inability of the prediction model to capture the natural variability. If SOM improved the prediction, we would see less variance about the on-to-line compared with constant. Addition of variable SOM has a minimal effect on the predictions (Fig 3; Table 3). As observed in the Saxton predictions, the mean for field capacity was improved for less than 1%, and the variance was improved by 4%. The mean for permanent wilting point was improved by less than 1% and the variance was improved by 11%. The mean for porosity was improved by less than one percent, but the variance was significantly improved by 87%. Figure 4 illustrates any improvement by including variable SOM in the Texas pedotransfer function. Again, there is very little shift of the red dots (variable SOM) toward the on-to-one line compared to the black dots. While Table 4 indicates some improvement in predicting porosity (r^2 increases by 0.08).

Saturated hydraulic conductivity (Ks) was predicted using Saxton and Rawls (2006) pedotransfer function. The inputs to the hydraulic conductivity pedotransfer function require some precursor calculations of other soil properties such as saturated soil moisture content. Predicted saturated soil moisture content (θ_s), using Saxton and Rawls (2006) pedotransfer function, overestimates the saturated moisture content affecting the Ks predictions. Since the dataset used did not contain measured data for saturated moisture content, we accepted the over estimation. The predictions of moisture content were then used for the saturated hydraulic conductivity predictions. Another component of the saturated hydraulic conductivity pedotransfer function is field capacity. The field capacity input used was the previously calculated predictions. Since field capacity was not significantly improved, saturated hydraulic conductivity was hypothesized not to be significantly improved.

Table 3. Summary statistics of Saxton and Rawls (2006) pedotransfer functions with sand (S, %), clay(C, %), and soil organic matter (SOM, %) held as a constant (1%) and allowed to vary as predictors.

	Field Capacity		Wilting Point		Porosity	
	S and C	SOM	S and C	SOM	S and C	SOM
R^2	0.71	0.71	0.87	0.87	0.17	0.43
RMSE (m^3m^{-3})	0.06	0.06	0.035	0.034	0.062	0.052
Bias (m^3m^{-3})	-0.018	-0.018	0.003	0.004	-0.026	-0.018

Table 4. Summary statistics of developed Texas pedotransfer functions with percent sand (S, %) and percent clay (C, %), and no soil organic matter (SOM, %) as predictors as well as with sand, clay and SOM as predictors.

	Field Capacity		Wilting Point		Porosity	
	No SOM	SOM	No SOM	SOM	No SOM	SOM
	--cm^3cm^{-3}---					
R^2	0.779	0.783	0.891	0.898	0.471	0.554
RMSE (m^3m^{-3})	0.052	0.052	0.0314	0.030	0.050	0.046
Bias (m^3m^{-3})	$2.740*10^{-16}$	$2.829*10^{-16}$	$7.786*10^{-17}$	$7.630*10^{-17}$	$-3.456*10^{-17}$	$-7.137*10^{-18}$

† MAXSMC, REFSMC, and WLTSMS are soil water contents in percent volume at 0 KPa, -33 KPa, -1500 KPa, respectively, and PAW is plant available water.

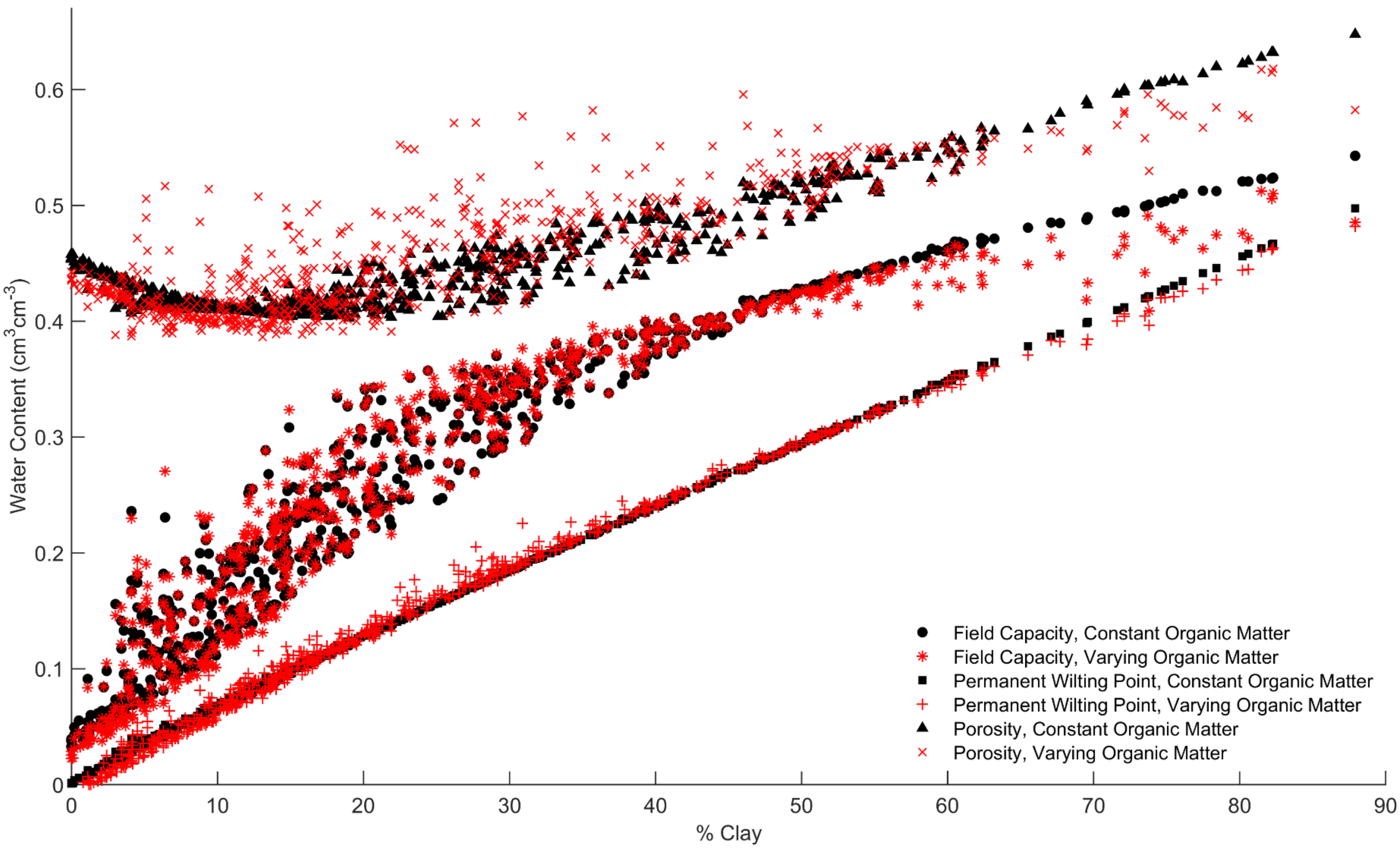

Figure 1. Saxton and Rawls (2006) pedotransfer functions to predict field capacity, permanent wilting point, and porosity using the National Cooperative Soil Characterization Database plotted with and without organic matter.

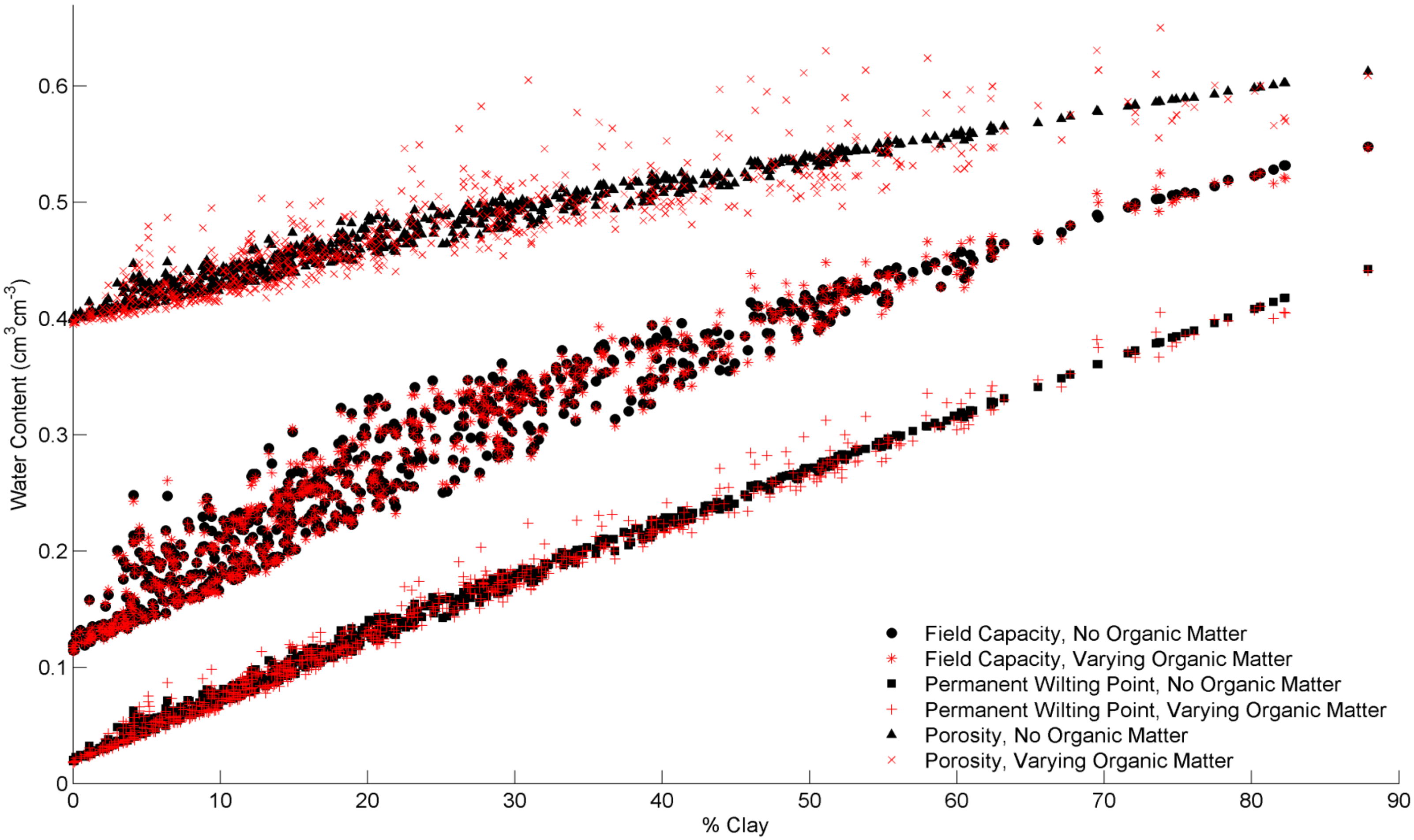

Figure 2. Newly developed pedotransfer functions to predict field capacity, permanent wilting point, and porosity using the National Cooperative Soil Characterization Database plotted with and without organic matter.

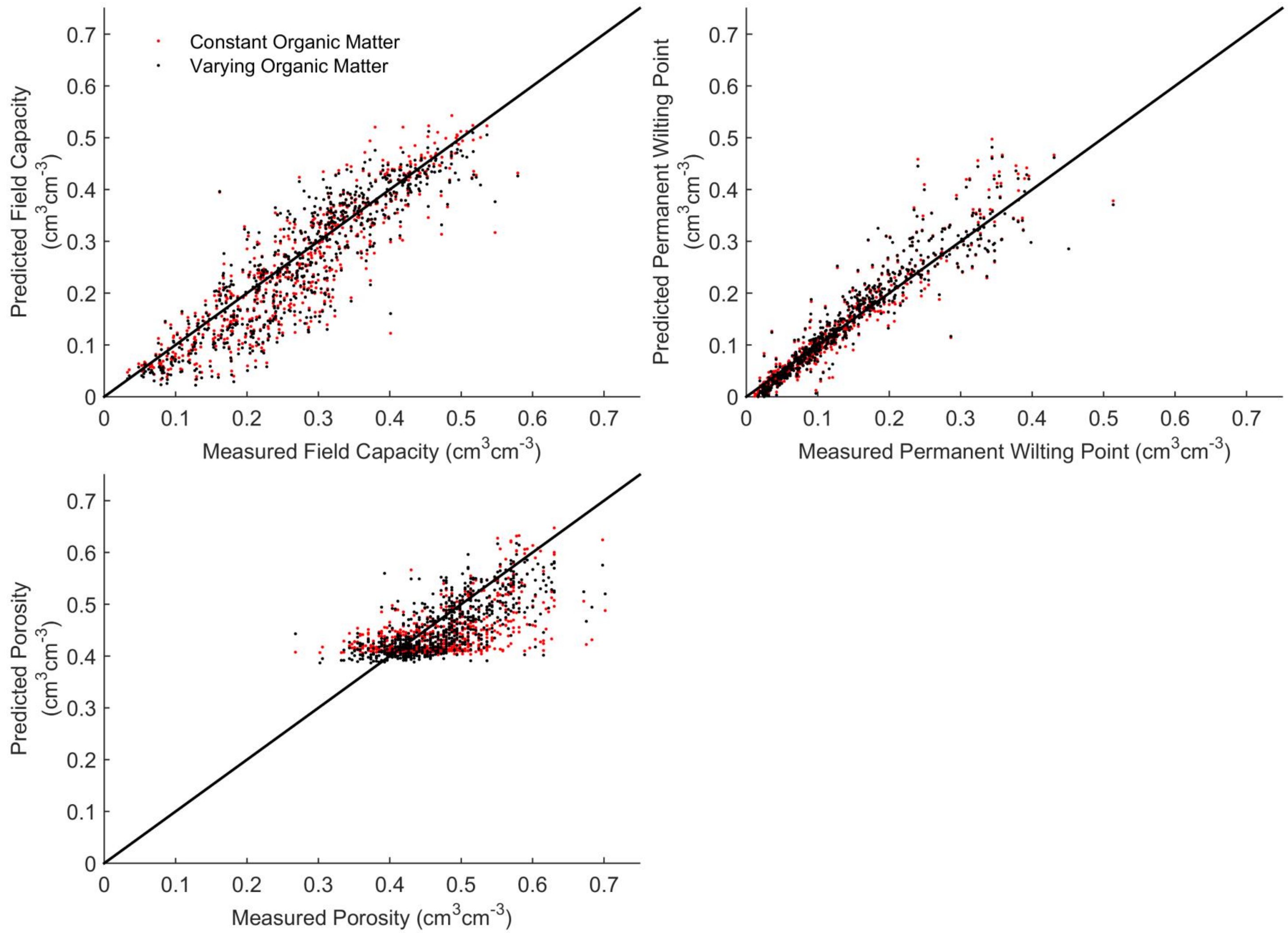

Figure 3 Summary of predictions from Saxton and Rawls pedotransfer functions using the National Cooperative Soil Characterization Database of permanent wilting point, field capacity, porosity, and plant available water with and without organic matter.

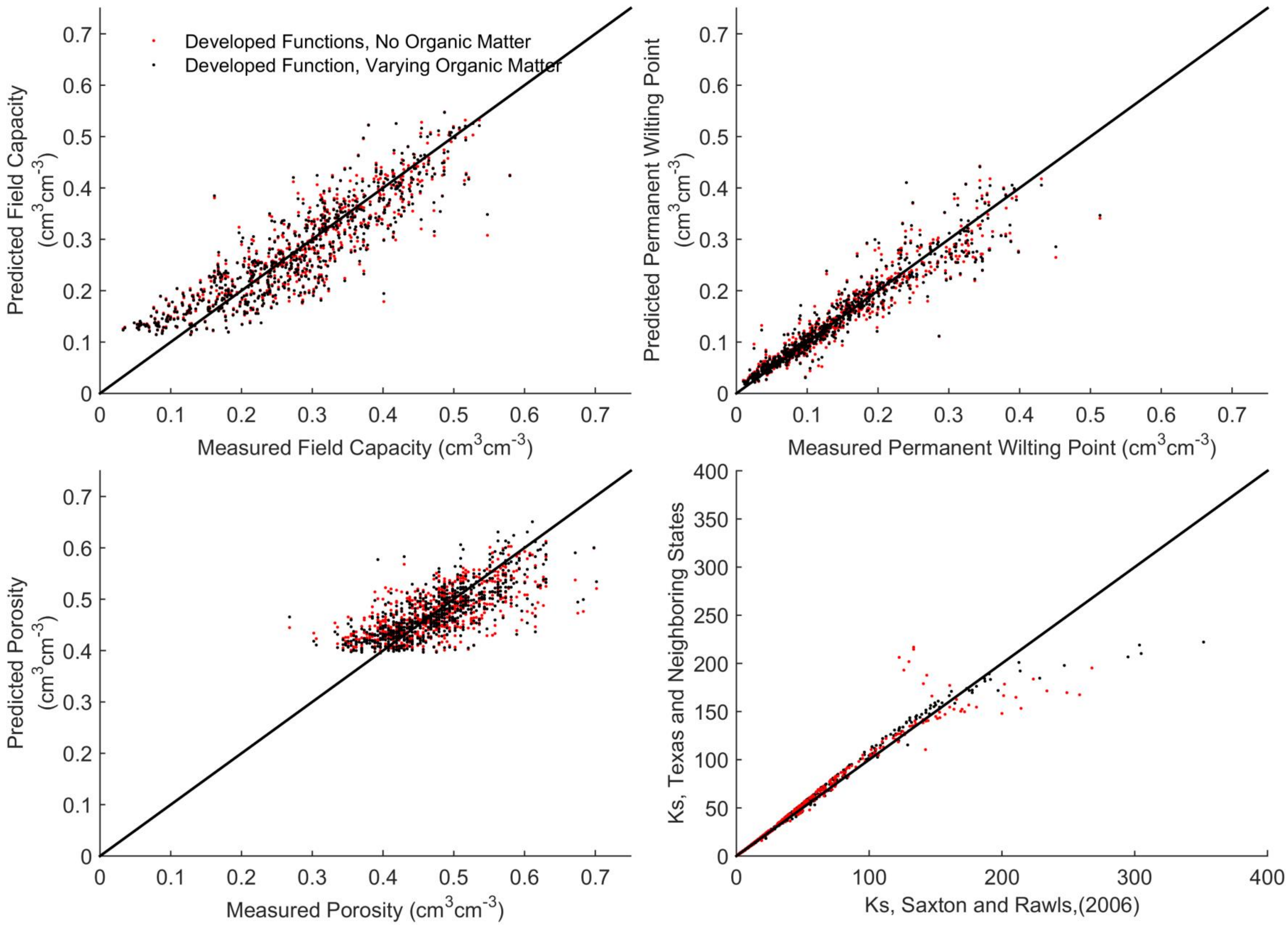

Figure 4. Summary of predictions from developed pedotransfer functions using the National Cooperative Soil Characterization Database of permanent wilting point, field capacity, porosity, and plant available water with and without organic matter.

CHAPTER IV

CONCLUSIONS

Though soil organic matter was statistically significant in Saxton and Rawls (2006) pedotransfer functions of soil hydraulic properties, only porosity was statistically significant in Texas pedotransfer functions. The overall change in prediction of field capacity and wilting point were small and changes in prediction values were functionally undetectable. Soil organic matter did improve predictions of porosity. Because predictions of soil porosity were meaningfully altered by the inclusion of variably SOM, the subsequent changes in predicting saturated hydraulic conductivity are likely more useful.

The literature is rich with information about how SOM affects soil till. In the soil science community, SOM is considered a primary indicator that the soil is healthy and function for water capture, storage, and plant growth. However our databases do not functionally reflect this interpretation of the science. Likely, this disconnect is more because of the measurement approaches that are used in developing the databases of soil hydraulic properties. As we know that SOM is crucial to the development of soil structure and aggregation, and soil structure and aggregation are key to soil function. If this wealth of knowledge about SOM and soil function are true, then we must conclude that the databases that are currently available are not adequate to capture the reality. Hence other approaches to converting easily-measurable soil properties to indices or values of soil hydraulic function are needed.

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